Management and Virtualization of Programmable Metasurfaces: Concept, Challenges and Prospects

Christos Liaskos[1], Kostas Katsalis[2], Joan Triay[2] and Stefan Schmid[3]
[1]University of Ioannina and FORTH, Greece, e-mail: cliaskos@ics.forth.gr
[2]DOCOMO Communications Laboratory GmbH, Munich, Germany, e-mail: katsalis, triay@docomolab-euro.com
[3]TU Berlin and Fraunhofer SIT, e-mail: stefan.schmid@tu-berlin.de

***Abstract*—Sixth generation (6G) communications are expected to enable the fusion of the digital world with the physical world, leading to possible unprecedented requirements on the timely and efficient management of communication and computing resources. Programmable metasurfaces (PMs) are a key 6G enabler, which allow programmatic control over the propagation of wireless waves in space. In this paper we study the problem of PMs virtualization, yielding their representation as softwarized cloud resources. We elaborate on how virtual PMs (VPMs) can be created and managed by unified resource management systems, in the light of multi-tenancy and network slicing. We analyze how VPMs enable the dynamic deployment of end-to-end services, promoting isolation even in the case of considering different performance objectives. Use cases, challenges and open questions are highlighted.**

***Index Terms*—6G, programmable metasurfaces, virtual programmable metasurfaces, NFV, cloud computing.**

I. Introduction

WHILE a certain level of maturity has been achieved regarding the deployment of 5G networks, both academia and the industry are trying to articulate the key requirements and supporting technologies which will be used to define and build the overall next-generation (6G) ecosystem. 6G is expected to span a wide set of enabling technologies, such as next generation MIMO, integrated sensing, distributed federated AI, and flexible programmable infrastructures. Thus, 6G raises the need for an efficient representation and unified management of the diverse communication resources [1].

A particularly interesting wireless resource for 6G are programmable metasurfaces (PMs). A programmable metasurface can be understood as a tile constructed using meta-materials that support manipulation of impinging electromagnetic waves. Based on the tile configuration specific actions can be performed like beamforming, signal absorption and polarization control [2]. An extensive use of PMs, not only for indoor, but also outdoor scenarios, is expected to yield increased channel capacity and throughput, coupled with advanced physical-layer isolation (i.e., security) [3].

Notably, the abstraction of the physics behind PMs and the interfacing with computing devices has been identified as an important problem early on [2]. Moreover, articulating this abstraction via Software Defined Networking (SDN) has also been investigated [3], porting the core SDN principle, i.e., making the high-level management logic of a network independent of the underlying hardware, to the PM case. Nevertheless, there exists a wide technical gap to be bridged between the state of the art and the needs by new 6G use cases and operator requirements. The related work so far is not tackling the problem of how programmable metasurfaces can be represented as abstracted and virtualized resources for the needs of modern communication systems, and, subsequently, no means are available to perform network slicing on top of metasurfaces from a network orchestration and management perspective.

Resource virtualization is about creating an abstraction layer over hardware resources using software [4]. This abstraction layer is used to facilitate the operation of softwarized resource management, isolating user groups into virtual systems that resemble the physical ones. For example, in the case of computing, a virtual machine (VM) is widely used for providing the same functionalities as a physical computer, while being offered as a software entity instead. Many such VMs can share the same physical computer resources, without users perceiving a difference. This concept of sharing can be extended beyond computer resources also into the network domain, in what is generally referred as network slicing, i.e., creating sets of isolated services, functions, and resources (physical or virtual) tailored to specific user groups and their respective needs, while efficiently sharing the same physical infrastructure [4].

In this paper, we introduce the concept of resource virtualization and management for PMs. Particularly, we propose the novel concept of Virtual Programmable Metasurfaces (VPMs) and we elaborate on: i) how they can be perceived as a new type of virtualization-compatible cloud resource, and ii) be integrated to modern resource management systems, such as ETSI NFV-MANO and O-RAN [5], [6]. Towards these ends, a PM Hypervisor (PMH) entity is introduced to abstract the underlying physical PMs and support the relevant life-cycle management operations for the VPMs. Exploiting best practices from SDN, Network Function Virtualization (NFV) and network slicing, we describe possible interactions between the PMH and network slice management and orchestration systems for the mobile network. We also illustrate how new functionality can be incorporated inside the network slicing management systems, when considering PMs and VPMs.

The proposed approach is compatible to any PMs technology [7], and to both indoor and outdoor deployments. Novel use cases exploiting the VPM concept towards 6G communications, like VPM migration and dynamic life-cycle management are presented, and several challenges and open questions are discussed.

II. Background and Related Work

Programmable metasurfaces (PMs): PMs are artificial materials with engineered and real-time tunable electromagnetic properties [2]. As such, they can provide tunable interaction with impinging waves that can be, e.g., steered, re-polarized and focused on a software-defined manner. PMs are the building blocks of the recently proposed Programmable Wireless Environments (PWEs) [8] and Smart Radio Environments (SREs) [9], which have similarities but generally target different deployment scale. However, the terms are typically used interchangeably in the literature.

PWEs comprise large sets of PMs and constitute a generic system for controlling any type of PM, in order to apply deterministic control over the wireless propagation process [8]. PWEs seek to provide a full protocol stack, clarifying the physical, network, control and application layers of the system, as well as its integration to the existing networking infrastructure via the SDN paradigm. PWEs focus on providing the necessary software abstractions for transforming the PWE real-time operation in an algorithmic problem on graph representations, while abstracting the underlying physics with event-driven software callbacks. Moreover, PWEs define the system workflow from the protocol perspective, from the discovery of a PWE by a user device, to the statement of objectives and to its service, providing algorithms to configure any set of PMs for any multi-user setting [3].

PWE as a generic control system of any PM technology (e.g., [7]) focus in providing the facilities for crafting electromagnetic vector field distributions in a space, encompassing derivative reductions, such as affecting the scalar power levels at a device. To this end, PWEs treat PMs in their most generic way of operation, i.e., converters of surface current distributions. Impinging waves create a surface distribution "A" upon a PM, and embedded control elements convert it to a state "B" that yields the required electromagnetic field as a global response. Importantly, multiplexing can occur by: i) dividing its surface into sub-areas, each with different functionality (e.g., steer, absorb), and/or ii) duty-cycling the PM. However, precise benchmarking must accompany each approach, as complex interactions among the PM constituent elements will have an impact on the efficiency of each functionality [10], [11].

SREs constitute a concept that focuses on the signal processing aspects of wireless communications, and especially in conjunction with machine learning techniques. The channel control type is stochastic (SREs typically assume very few PMs, sparsely deployed within a space, and in the far field in general) and the employed PM technology is specific to reflect arrays, which are commonly denoted as intelligent reflective surfaces (LIS, IRS or RIS). Based on these premises, the goal is to iteratively optimize the reflect array phase shifter states (free variables) to maximize a scalar quantity representing a wireless communication objective (e.g., fitness function). Additionally, given the theoretical signal processing focus of SREs, the required protocols, system workflows and integration-to-infrastructure processes are commonly left undefined in the literature, i.e., inherently assuming that an underlying PWE system stack or similar is in place. In a layered sense, PWE is a top-to-bottom systemic approach, while the SRE is a layer-specific approach (channel modeling with reflect arrays). In the following, we consider that PMs encompass any technology, i.e., covering both metasurfaces and reflect arrays.

Recently a newly formed Industry Specification Group (ISG) on Reconfigurable Intelligent Surfaces (RIS) has been established to investigate the relevant use cases and requirements as well as the design of an end-to-end architecture considering RIS elements [12].

Table I summarizes the terminology used in this work and the key technical dimensions to consider regarding programmable metasurfaces.

TABLE I
KEY ASPECTS OF PROGRAMMABLE METASURFACES AND TERMINOLOGY USED

Characteristic	Description
Operating Principle	• RIS, LIS, SM, SMM: λ/2-λ/4 antenna arrays and reflectarrays. • SDM, HSF: Metasurfaces, programmable surface current, meta-gratings
Taxonomy	• Non-wavefront amplifying/passive vs Wavefront-amplifying/active • Near-field/vector field-crafting vs Far-field/reflection pattern-crafting • Autonomic vs externally controlled • Self-powered (energy harvesting) vs externally-powered • Ultra-thin/transparent vs electromagnetically-thin/opaque
Wave manipulation types	Custom redirection (reflection, diffraction, towards single or multiple directions, i.e., splitting and scattering), power alteration (amplify, partially attenuate, fully absorb), polarization modification, phase modification, frequency filtering, collimation, arbitrary departing wavefront crafting, re-modulation.
Sharing approaches per surface unit	Spatial separation per wave manipulation type, wave manipulation type interleaving, time-varying manipulation types (faster or slower than the wavelength of the manipulated impinging wave).
Operating frequency and bandwidth	1-20GHz is well-studied, mmWave is under practical research focus and extensive prototyping, THz is under sustained exploration by employing Graphene as the enabling material. Bandwidth: both narrow-band and wider-band designs exist, trading manipulation efficiency for wider operating bandwidth
Programmability and control	Hypervisor for hosting wave manipulation types (SDMs), enforced by electronic control elements embedded in the surface. • Simplest approach: plain PIN diodes directly controlled by an embedded IoT gateway, • most advanced approach: embedded ASICs within the metasurface cells, with intra-communication capabilities for synergetic operation and robust control, connected to the external world via an embedded IoT gateway)
Terminology	
Network Management	Software Defined Networking (SDN) , Network Function Virtualization (NFV), Network Service (NS), Physical Network Function (PNF), Virtual Network Function (VNF), Network Slice Management Function (NSMF)
Metasurfaces	Reflective Intelligent Surface (RIS), Large Intelligent Surface (LIS), Software-Defined Metasurface (SDM), HyperSurface (HSF), Smart Mirror (SM), Spatial Microwave Modulator (SMM), Virtual Programmable Metasurface (VPM)

Network Slicing: 3GPP TS 23.501 specifies the relevant entities and functionalities used to enable network slicing on a mobile network. 3GPP also defined several management entities in 3GPP TR 28.801 regarding the management of Network Slice Instances (NSIs). The initial studies about network slice life-cycle management aspects from 3GPP TR 28.801

were progressed since Rel-16 in several specifications, like 3GPP TS 28.530 and 3GPP TS 28.533. For example, 3GPP TS 28.530 describes the requirements for the transition to a service-based slice management architecture. Recent research activities are about extending network slicing management with AI technologies to support intelligent network management [13].

The authors in [3] investigate the case of sharing PMs resources using SDN logic to multiple tenants. While the significance of software orchestration and resource management has been acknowledged, no work has gone beyond simple interfaces to directly control the state of the embedded elements.

In our approach, similarly to the case of VMs, VPMs can operate on top of programmable metasurfaces and can also be part of NSIs. A static model of interacting with a PM through a gateway system will be difficult to manage and maintain due to its lack of flexibility, even though it is expected to be a starting point of integrating the technology inside the mobile network. With the introduction of a virtualization layer on top of the PM, best practices from cloud computing, SDN/NFV and Radio Access Network (RAN) virtualization can be exploited, not only for improving resource utilization but also creating new market opportunities, with new stakeholders and new vendors offering fascinating services on top of programmable metasurfaces.

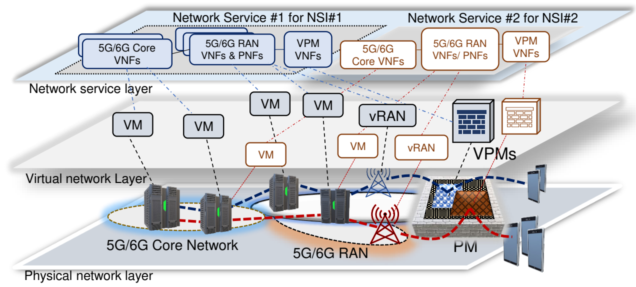

Fig. 1. Example of two network services belonging to different NSIs sharing a common set of physical infrastructures.

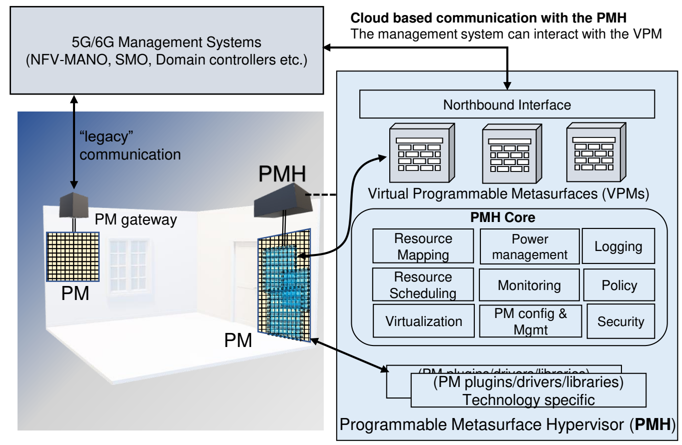

Fig. 2. PM hypervisor (PMH) architecture.

III. Virtual Programmable Metasurfaces

A. The Concept of Virtual Programmable Metasurfaces

A Virtual Programmable Metasurface (VPM) is a logical and virtual environment implemented as a software entity that provides the same functionality as a PM to the metasurface control and management entities. While in the data plane the end user terminal (e.g., mobile phone) is receiving signals from the PM, in the management and control planes VPMs represent a specific set of PM resources which can be managed and controlled on a per VPM basis.

In our approach, VPMs are created and managed by a PM hypervisor function (PMH). A PMH resembles the properties of OS and network hypervisors [14], or other physical layer sharing mechanisms as a new type of resource sharing and resource management mechanism. Physical resources in a PM can span multiple domains: spatial domain (parts of the tile), frequency domain (specific frequencies which can be allocated to a tenant/slice), phase domain, time domain, etc. The PMH system is used to create an abstraction layer on top of these physical resources and enable resource sharing between multiple VPMs.

A visual representation of an envisioned 6G mobile network services when considering VPMs is depicted in Fig. 1. Besides the 5G/6G RAN and Core network functions, additional network functions are considered, deployed on top of VPMs. In the light of network slicing, this new type of network services leveraging PMs or VPMs can be used to realize part of one or more network slice instances.

B. The PM Hypervisor (PMH) System

From an architectural perspective the PMH provides a set of core functionalities, while it also exposes a northbound API for the management of both PMs and VPMs and a southbound interface for the actual management and configuration of the multi-technology PMs. A visual representation of the PMH architecture is provided in Fig. 2.

- *PMH Core*: it comprises the functions of PM virtualization and supports VPMs life-cycle management operations (create, delete, scale, migrate, etc.). PMs can be virtualized considering multiple forms of multiplexing, such as in space and time, or in space and frequency domain. As a VPM operates by using PM resources, the main responsibility of the PMH core is to perform resource mapping and resource scheduling (i.e., which resources are allocated to the VPM) to support VPMs multiplexing. PMH Core is responsible for preserving VPMs isolation (guarantees that there are no conflicts due to multiplexing). Highly complex operations by means of resource scheduling are expected to support such functionalities. Furthermore, PMH Core correlates data and statistics received from the PM tile with VPMs. It is also responsible for operations like logging information, notifications sending, monitoring, policy management, security and power management for both PMs and VPMs. Additional functionality like VPM snapshotting and high availability can also be considered.

- *Northbound interface*: it is used to expose functionality related to PMs and VPMs management. For example, the interface exposes inventory services of the PM and VPM resources to the northbound. It also provides PMs capabilities exposure and capacity management, as well as management related capabilities to support service requests for VPM life-cycle related operations. It can also expose filtered performance/fault management data for both the VPMs and the PMs. The northbound API can be used by dedicated PMs management systems (e.g., acting as RAN domain controllers). This interface could be realized in the form of some standard RESTful-based API or SDK. Instead of managing the PM directly like in a "legacy" gateway system approach, a management system can now manage the VPM by using the northbound interfaces exposed by the PMH, but with added resource sharing capabilities and simpler management thanks to the PMH enabled abstractions.
- *Communications in the southbound*: in the southbound a set of interfaces are used for the actual PMs configuration and management. The PMH system collects and analyzes performance and fault management data from the PMs. This interface could be realized in the form of plugins, drivers, etc.

Finally, it is worth mentioning that the SDN-based solution presented in [3] could operate on top of the PMH for the control of VPMs.

IV. Network Slicing and Management of Virtual Programmable Metasurfaces

A. Slicing in 3GPP and ETSI NFV

According to 3GPP (e.g., 3GPP TS 28.530 and 3GPP TS 28.533), RAN Network Slice Subnet Management Function (NSSMF) handles the slicing management when considering RAN network functions (NFs), TN-NSSMF is about slicing management when considering Transport Network elements, and CN-NSSMF handles the slicing management for Core Network (CN) NFs. Network Slice Management Function (NSMF) is used for the end-to-end management and orchestration of the NSIs. PNFs and VNFs together with the underlying physical resources are used to compose netwrok services which can be mapped to one or more NSIs.

Following the same principles of operation like in the case of compute node virtualization, the PMH is slice-unaware but the VPMs can be part of an NS which can be mapped to one or more NSIs. Under network slicing an NS can utilize multiple associated VPMs, with the corresponding VNFs wired to the rest of the PNFs and VNFs. Each VPM may be built using a different physical layer characteristic. Sharing VPMs is also possible between different NSIs.

B. Rethinking the Network Slicing Management Plane

Although metasurfaces can in principle be seen and understood as a pure radio resource, the management of physical environment type of resources has not been yet considered by RAN-NSSMF. New functionality inside the telecom operator's

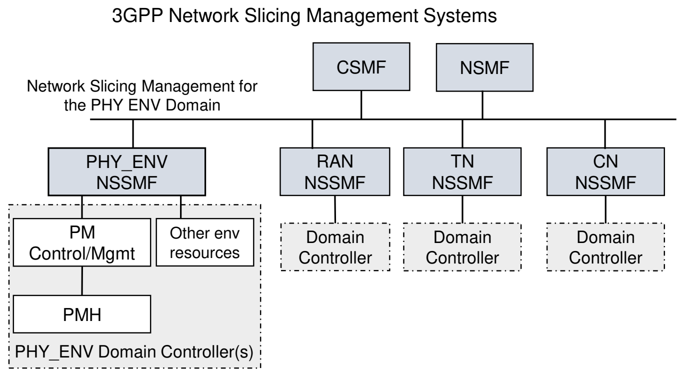

Fig. 3. New PHY_ENV NSSMF managing metasurfaces and other physical environment resources and functions.

network slice management systems is necessary to support the life-cycle management of NSIs comprising VPMs hosted by and operating on top of shared PMs. For example, to associate/de-associate VPMs and the corresponding VNFs with a NSI and a network service. Two possible options, which advance the available network slice management plane to support this new type of functionality, can be considered:

- *Option 1 (new management entity for physical environment related resources/functions):* The solution defines a new NSSMF (named PHY_ENV-NSSMF) which is used to manage physical environment related aspects of the NSI. PHY_ENV-NSSMF can manage any type of environment related resources and can be used to support several additional use cases [8]. The PHY_ENV-NSSMF enables the capability to use different environment resources to support multiple NSIs (e.g., one NSI is optimized for sensing, one NSI is optimized for beamforming optimization, etc.). See Fig. 3 for a visual representation of the proposed management solution.
- *Option 2 (extending the scope of RAN-NSSMF):* The scope of RAN-NSSMF is extended to also cover the management of NSIs aspects associated to physical or virtual programmable metasurfaces.

In both cases the overall management of the VPMs can be made using the PMH while the actual configuration and management of the VPMs/PMs is made through the corresponding domain controllers interacting with the PMH. When considering NFV technologies, similarly to VM-based or container-based environments, the PMs/VPMs resources as well as the relevant VNFs/PNFs are managed by an orchestrator (e.g., ETSI NFV's NFV-MANO NFVO, O-RAN SMO etc. [5]). ETSI GR NFV-IFA 046 report provides a detailed analysis of possible architectural mapping options between ETSI NFV and the O-RAN architectural frameworks [6]. Note that the concept of VPMs can be exploited in the general case, without considering necessarily network slicing.

In Fig. 4 on the left-hand side 3GPP network slicing management entities together with ETSI NFV's NFV-MANO are depicted. In the middle 3GPP network slicing management entities together with ETSI NFV's NFV-MANO and O-RAN SMO are depicted. In the latter design PMs and VPMs can be also considered as part of the O-Cloud as an additional

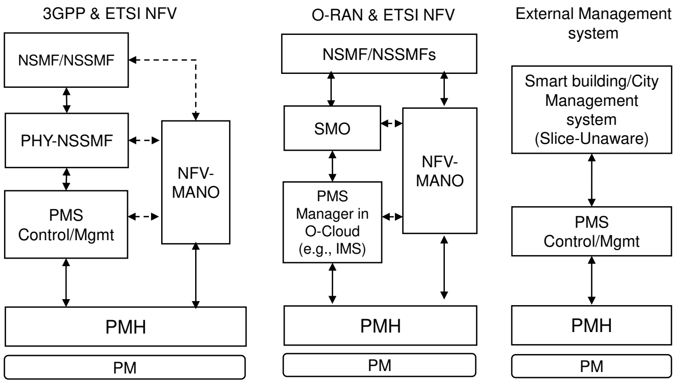

Fig. 4. Orchestration and management of VPMs.

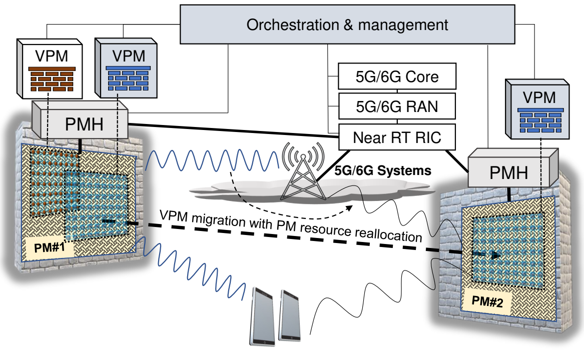

Fig. 5. VPM migration use case.

type of virtualized resources. On the right-hand side VPMs created and controlled by the PMH are managed by an external management system (like for example a Smart Building management system).

V. Use-cases and New Cloud Operations

Embracing VPMs as a new type of virtualized cloud resource can be a driver for substantial improvements on the way telecom networks are designed and operated. Greater levels of flexibility and novel use cases can be envisioned by exploiting VPMs. Note that VPMs concept is not tailored only to a specific type of access network and is equally applicable to 3GPP and non-3GPP access types.

A. Examples of New Cloud Operations

VPM migration: During design time and instantiation a VPM is mapped to a set of PM resources. During operation, and to maximize the multiplexing gains for a number of co-operated NSIs, VPMs migration is an additional operational action to consider, depending on the policies in effect. The VPM object status (operational and configuration data) needs to be preserved even after instantiating on top of another PM. In Fig. 5 a VPM is migrated from one PMH to another PMH. The appropriate resource allocation on the target PM is performed together with the necessary signal steering on the RAN part, supported by a Near Real Time Controller (Near-RT RIC) [5] to point to the appropriate PM.

VPM scaling: As in the case of VMs and the hosted VNFs, when it comes to increased load conditions, it is legitimate to assume that dynamic scaling operations are also possible for VPMs. Scaling can be related to more than one dimension. For example, to scale up a VPM we may adjust at the same time the frequency spectrum in the frequency domain and allocate a wider area on the tile to the VPMs in the spatial domain.

B. Use-cases related to VPMs

As surveyed in [8] several deployment scenarios and 6G use cases can be envisioned for indoor and outdoor environments, public or private networks, (e.g., industrial networks, smart homes, smart hospitals, etc.). Some indicative use cases, when considering the use of VPMs are the following:

Ultra-low-latency wireless communications: Since VPMs can perform resource slicing over services offered by underlying systems such as PWEs and SREs, they can keep the wireless waves concentrated within air-routes, thus: i) extending their range, and ii) avoiding interference and eavesdropping at the physical layer. As such, VPMs can in principle replace via resource scheduling: i) the medium access and network layer mechanisms, and ii) even some cryptographic services of the application layer. Recently, this has been found to facilitate ultra-low-latency applications such as virtual and extended reality [15]. With the proposed scheme, in the light of network slicing, a slice tenant may request VPM resources with specific ultra-low-latency requirements, while another tenant may request VPM resources to support extended wireless coverage.

3GPP and non-3GPP access: In a single area both 3GPP and non-3GPP access (e.g., Wi-Fi) types can be used to support end-user connectivity. 3GPP and non-3GPP access convergence has already been achieved, see 3GPP TS 23.501. In such an environment, a PM can be used to manipulate the electromagnetic waves for both types of networks. Therefore, when virtualizing the PM, it would be perfectly feasible to assume a set of VPMs to be managed by the non-3GPP system (e.g., Wi-Fi) and another set by the 3GPP control and management systems.

VPMs and virtualized RAN: O-RAN standards are about softwarizing RAN based on two main pillars: running the RAN protocol stack in software and exploiting the microservices concept by disaggregating the RAN into more granular network functions. O-RAN specifications are aligned with 3GPP work, but also go beyond by developing new functionalities like AI-based RAN Intelligent Controller (RIC) and the Service Management and Orchestration (SMO) [5]. In an O-RAN environment, the overall control and management of VPMs migration (see Fig. 5) could be facilitated using the near-Real Time (RT) RIC, which is able to interact with all the RAN functions, regardless of being virtualized or not. Depending on operational data like system load, user mobility, and interference management policies in effect, sophisticated decision making could also consider the appropriate VPMs resource migration.

Advanced access security: Depending on the technology in effect, one of the capabilities of a PM is to completely absorb the electromagnetic waves. With the proper security control mechanisms, communications can be dynamically tuned to enable security from the the VPM/PM level up to the application layer.

VI. Challenges and Open Questions

In principle the physical layer characteristics of the PMS technology are not impacted by the proposed scheme and the introduction of PMH. Nevertheless, specialized configuration may have an impact on the performance expected by each tenant/user of the virtual PMSs and optimal configuration is required to maximize the multiplexing gains. In the following we describe key issues related to the use of VPMs.

- Complicated interactions due to the operation of multiple VPMs are expected. Compared to classic resource virtualization architectures, VPMs pose fairly different algorithmic and optimization challenges, accounting for geometric constraints and supporting more dynamic reconfigurations.
- Sophisticated algorithms are required for the efficient reconfiguration of metasurfaces, e.g., due to policy changes, or the mobility of users or even the metasurfaces themselves (e.g., when mounted on drones).
- An optimal resource utilization requires algorithms for an accurate demand prediction (e.g., using sampling and AI) as well as for striking a good tradeoff between, e.g., providing isolation between tenants and making efficient use of opportunistically available channel capacity. In general, the algorithms should typically be online. Efficient resource usage further requires algorithms for tight synchronization between transmitting devices, tiles and receivers.
- Isolation guarantees to avoid VPM users being impacted on the use of PM elements from other VPM user in more complex scenarios needs further investigation. Especially when operating in non-trivial radio environments (i.e., not in free space) with scattering objects, there will be complex reverberation-induced long-range coupling between different "slices" of the PMS [8].
- To maximize the multiplexing gains sophisticated network embedding and admission control algorithms need to be devised when considering the operation of VPMs. The applicability of existing or the design of new efficient scheduling algorithms will precipitate the adoption of the concept towards 6G.
- Considering PMs and VPMs as cloud resources creates plausible questions regarding the management domain boundaries. For example, how to coordinate legacy RAN elements management with the life-cycle management (e.g., deployment, instantiation, operation, termination) of this new type of virtualized resources is an open issue.
- Performance analysis when sharing PM resources between multiple tenants in the light of network slicing has not been performed and depends on the type of the PM resource which is virtualized and shared.
- Following ETSI NFV methodologies, VPMs could be defined in a resource descriptor and thus be also considered as a cloud resource. How a VPM can be described so it can be onboarded to a cloud system and how full management can be supported needs further investigation.
- How to achieve coordination with the radio transmitting part from the RAN (e.g., for achieving throughput maximization, interference minimization etc.), when considering virtual metasurfaces is for further investigation. New highly complex joint optimization problems are expected to arise.

Other open issues are related to end-to-end network services, network slices and security management when considering the overall RAN part, including both wireless and wired connections. Network service health monitoring mechanisms, like also administration and management (OAM) for PMs and VPMs, are open issues which may unleash the potential for extensive research on the field. Best practices from cloud computing and mobile network management are expected to be considered to address issues related to the management of large-scale massive PMS and VPMs deployments.

VII. Conclusion

In this work we presented the concept of virtual programmable metasurfaces in the light of network slicing. We elaborated on how virtual programmable metasurfaces can be turned into a new kind of cloud resource. We also described how virtual programmable metasurfaces can be managed uniformly from the network operator as part of end-to-end telecom network services on a multi-technology operational environment (e.g., 3GPP-based and non-3GPP access).

As the PM technology still evolves, the concept of exposing and managing virtual programmable metasurfaces as a new type of cloud resource, can be exploited by third parties for the design of solutions tailored to novel 6G use cases.

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Christos Liaskos received the Diploma degree and the Ph.D. degree in computer networking from the from the Aristotle University of Thessaloniki (AUTH), Greece. He is currently an Assistant Professor with the University of Ioannina and an Affiliated Researcher with the Foundation for Research and Technology Hellas (FORTH), Greece, working on 6G technologies.

Kostas Katsalis received the Diploma degree in Electrical and Computer Engineering from University of Patras, Greece in 2005, and a PhD degree from the Department of ECE, University of Thessaly, Greece. He is a network architect and standardization specialist at Docomo Euro-labs, Germany.

Dr. Joan Triay received his B.Eng., M.Eng. and Ph.D. degree in telematics engineering from the Universitat Politecnica de Catalunya (UPC, BarcelonaTech), Barcelona, Spain, in 2006, 2007 and 2011, respectively. Currently, he is a network architect and manager at DOCOMO Euro-Labs, Germany.

Stefan Schmid received the M.Sc. degree in computer science from ETH Zurich, Switzerland, in 2004, and the Ph.D. degree in distributed computing from ETH Zurich, in 2018. He is currently a Full Professor with TU Berlin, Germany, and an Affiliated Researcher with Fraunhofer SIT, Germany, working on distributed systems, networks, and algorithms.